NAG 2-329
NAGW-665

THE RED AND GREEN LINES OF ATOMIC OXYGEN IN THE NIGHTGLOW OF VENUS

7N-91-CR
252391
6P

J. L. Fox

Institute for Atmospheric Sciences
and
Department of Mechanical Engineering
State University of New York at Stony Brook
Stony Brook, NY 11794

ABSTRACT

$O(^1D)$ and $O(^1S)$, the excited states that give rise to the atomic oxygen red and green lines, are produced in the Venus nightglow in dissociative recombination of O_2^+. The emissions should also be excited by precipitation of soft electrons, the suggested source of the "auroral" emission features of atomic oxygen at 1304 and 1356 Å, which have been reported from observations of the Pioneer Venus Orbiter Ultraviolet Spectrometer. No emission at 6300 or 5577 Å was detected, however, by the visible spectrophotometers on the Soviet spacecraft Veneras 9 and 10 and upper limits have been placed on the intensities of these features. Here we evaluate the constraints placed on models for the auroral production mechanism by the Venera upper limits by modeling the intensities of the red and green lines in the nightglow. We combine a model for the vibrational distribution of O_2^+ on the nightside of Venus with rate coefficients recently computed by Guberman for production of $O(^1S)$ and $O(^1D)$ in dissociative recombination of O_2^+ from different vibrational levels. The integrated overhead intensities are 1 – 2 R for the green line and about 46 R for the red line.

INTRODUCTION

The Pioneer Venus Orbiter (PVO) Ultraviolet Spectrometer has detected emission features of atomic oxygen at 1304 and 1356 Å on the nightside of Venus /1/. The 1304 Å feature appears with a typical brightness of about 20 R, but excursions to near 100 R have been observed. Fox and Stewart /2/ have suggested that the emissions are due to the precipitation of very soft electrons (energies on the order of a few eV) into the nightside thermosphere. Suprathermal electrons with an energy spectrum approximating a Maxwellian distribution with a characteristic energy of about 14 eV have been detected outside the atmosphere by the PVO Retarding Potential Analyzer/3/; energetic electrons have also been detected by the plasma analyzers on the Soviet spacecraft Veneras 9 and 10 /4/. Precipitation of such electrons should also excite atomic oxygen to the ^1S and ^1D states, producing emission in the green and red lines at 5577 and 6300 Å. The Venera 9 and 10 fly-by spacecraft carried visible spectrophotometers, but no 5577 or 6300 Å emission was measured on the nightside. An upper limit of 10 R has been placed on the intensity of the green line /5/; the sensitivity of the spectrophotometer at 6300 Å was about half that at 5577 Å and an upper limit for the red line intensity is about 20-25 R (Krasnopol'sky, private communication, 1988). These upper limits provide additional constraints on models for the auroral production mechanism. In order to evaluate these constraints, it is necessary to predict the rate of production of the green and red lines from other sources. Dissociative recombination of O_2^+

$$O_2{}^+(v) + e \rightarrow O(^1S,^1D,^3P) + O(^1D,^3P) \qquad (1)$$

is probably the most important source of these emissions in the nightglow. The yields of $O(^1S)$ and $O(^1D)$ have been shown to depend on the vibrational quantum number of O_2^+ /6,7,8/. Guberman has performed *ab initio* calculations of the rate coefficients for production of $O(^1D)$ and $O(^1S)$ in reaction (1) and he has shown, in particular, that the rate coefficient for production of $O(^1S)$ increases nearly two orders of magnitude from $v = 0$ to $v = 2$ /7,8/. We have constructed a model of the nightside ionosphere of Venus, and of the vibrational distribution of $O_2^+(v)$, and we have used Guberman's rate coefficients to predict the intensities of the red and green lines in the Venus nightglow.

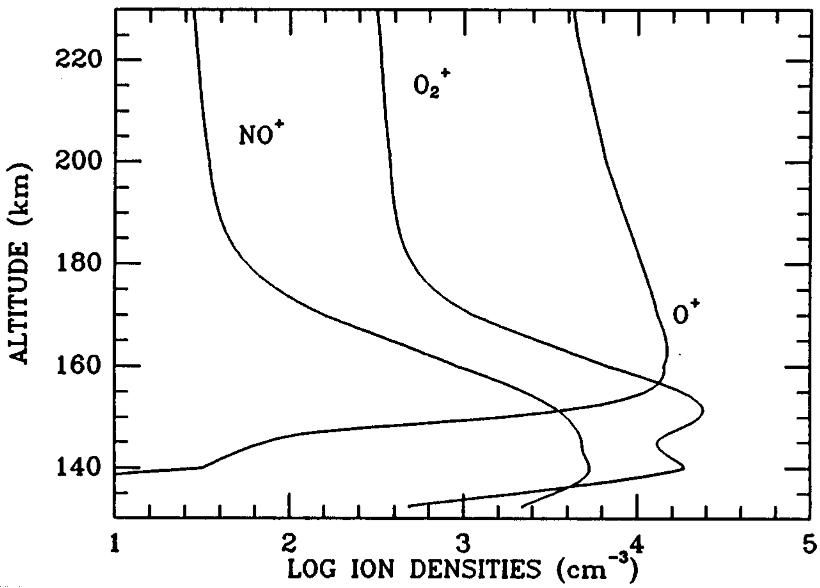

Fig. 1. Computed profiles for the major ion densities in the nightside ionosphere of Venus. The model was constructed by introducing a flux of O^+ of $1.0 \times 10^8 \mathrm{cm}^{-2}\mathrm{s}^{-1}$ at the top of the neutral atmosphere.

THE MODEL

Our model atmosphere consists of neutral densities and temperatures taken from Hedin et al./9/ for 165° solar zenith angle and $F_{10.7} = 200$; ion and electron temperatures are from the Venus International Reference Atmosphere /10/. The nightside ionosphere is maintained, at least at times of high solar activity, largely by transport of atomic ions, primarily O^+, from the dayside ionosphere /11,12,13,14/. The nightside ionosphere is, however, highly variable, sometimes disappearing completely /15,16,17/. Our model ionosphere is designed to represent "full-up" relatively undisturbed conditions, when we expect the rate of reaction (1) to be substantial, although not necessarily a maximum. We have modeled this ionosphere by introducing a flux of O^+ of $1.0 \times 10^8 \mathrm{cm}^{-2}\mathrm{s}^{-1}$ at the top of our model thermosphere. Computed altitude profiles of O^+, O_2^+ and NO^+ are shown in Figure 1. The effect of drag on the upward diffusion of molecular ions by the downward flux of O^+ is included in an approximate way by reducing the diffusion coefficients of the molecular ions by a factor of 10 to reproduce the shape of the measured O_2^+ profiles presented by Taylor et al./18/

The sources and sinks of vibrationally excited O_2^+ in the dayside thermosphere of Venus have been presented previously /19/. The major production reaction on the nightside is

$$O^+ + CO_2 \rightarrow O_2^+(v \leq 5) + CO, \tag{2}$$

while that on the dayside is

$$CO_2^+ + O \rightarrow O_2^+(v \leq 6) + CO. \tag{3}$$

The rate coefficients adopted here are the same as those used in the dayside calculations /19/. The nascent vibrational distributions produced in these reactions are unknown, so the energetically accessible vibrational levels are assumed to be populated equally. Fluorescent scattering was found to be unimportant for O_2^+ on the dayside; we therefore expect the steady state vibrational distribution on the nightside to be similar to that computed for the dayside. Loss of O_2^+ is mostly by dissociative recombination, reaction (1), but in the lower ionosphere reactions with N and NO producing NO^+ are also important.

In addition to the net sources and sinks of O_2^+, there are mechanisms, such as vibrational quenching, that merely act to interchange vibrational levels. In the lower ionosphere, the most important quencher is CO_2; it reacts with a rate coefficient $1 - 2 \times 10^{-10} \mathrm{cm}^3\mathrm{s}^{-1}$ /20/. Quenching by atomic oxygen

$$O_2^+(v) + O \rightarrow O_2^+(v-1) + O \tag{4}$$

is probably more important at high altitudes, but the rate coefficient and the average number of vibrational

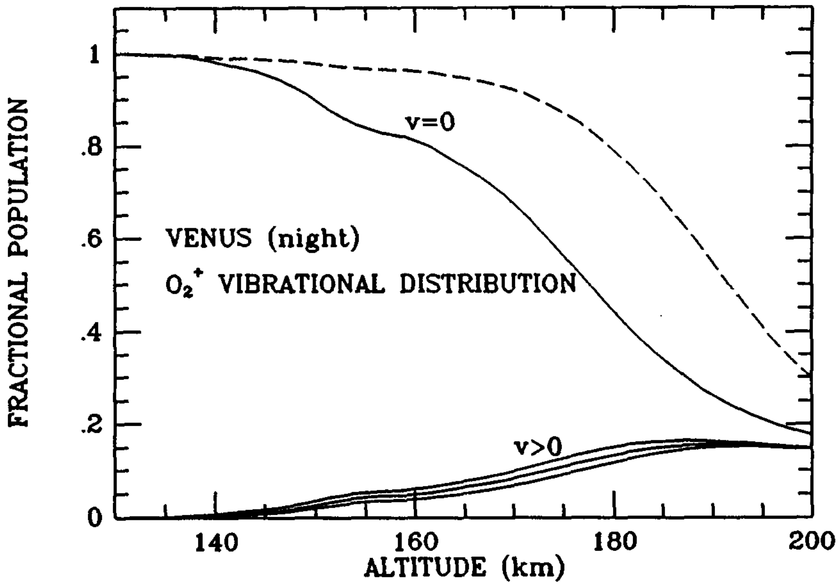

Fig. 2. Fractions of O_2^+ ions in vibrational states $v = 0 - 3$ as a function of altitude calculated with a photochemical steady state model, with an assumed value for k_4 of $1 \times 10^{-10} \mathrm{cm}^3\mathrm{s}^{-1}$. The curves labeled $v > 0$ are, from top to bottom, $v = 1$, $v = 2$, and $v = 3$. The dashed line is the fraction in $v = 0$ for $k_4 = 6 \times 10^{-10} \mathrm{cm}^3\mathrm{s}^{-1}$.

quanta lost are unknown. We assume initially that one quantum is lost and vary the rate coefficient from a standard rate of $1 \times 10^{-10} \mathrm{cm}^3\mathrm{s}^{-1}$ to as nearly gas kinetic value of $6 \times 10^{-10} \mathrm{cm}^3\mathrm{s}^{-1}$. Collisional excitation is the reverse of quenching and the rate coefficient is related to that for quenching by detailed balance.

RESULTS AND DISCUSSION

We have solved the continuity equations for O_2^+, taking into account vibrational levels $v = 0 - 60$ of the ground electronic state, as we have done for the terrestrial atmosphere /21/. Figure 2 shows the fractions of O_2^+ in the first four vibrational levels as a function of altitude from 130 km to 200 km. The calculation of the vibrational distribution assumes photochemical equilibrium, which is valid below about 160-170 km. The ions at higher altitudes are produced largely by transport from below. The dashed line shows the fraction in $v = 0$ for the larger rate coefficient for reaction (4). The vibrational distributions are combined with the rate coefficients from Guberman /7,8/ and the total dissociative recombination coefficient from Alge et al./22/ to give the yields for $O(^1S)$ and $O(^1D)$. For dissociative recombination from vibrational levels for which no information is available, the rate coefficient is assumed to be equal to that for the highest level for which data are available. Altitude profiles of the yields and the volume emission rates are shown in Figures 3 and 4, respectively. The $O(^1S)$ yield varies from much less than 1% to about 8% at high altitudes. Figure 4 shows that most of the emission arises between 140 and 160 km where the ^1S yield is less than 2%. The dashed lines show the yields and volume emission rates for the assumption of the larger value for k_4. The integrated overhead intensity of the green line is about 1.2 R for the standard quenching rate and 0.5 R for the larger quenching rate. Since the model ionosphere chosen has a peak electron density near the average observed nightside value /23/, the upper limit for auroral production of the green line is probably close the the reported upper limit. A flux of soft electrons of sufficient magnitude to produce the observed 1304 and 1356 Å intensities produces 4 to 7 R of 5577 Å emission /2/. Thus the green line intensity from O_2^+ dissociative recombination does not affect the viability of the soft electron mechanism. We have found, however, that if the reaction

$$N + O_2^+ \rightarrow NO^+ + O, \tag{5}$$

which is the major source of NO^+ on both the dayside /24/ and the nightside /25/ of Venus, produces $O(^1S)$ with an efficiency near 20%, as has been suggested from terrestrial studies /26,27/, the integrated intensity increases to 17 R, a value significantly larger than the reported upper limit.

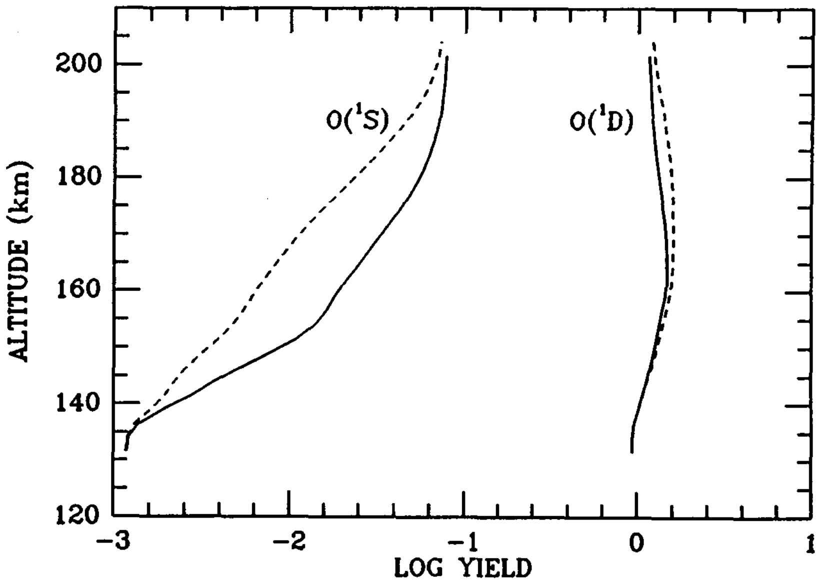

Fig. 3. Altitude profiles of the yields of $O(^1S)$ and $O(^1D)$ produced in dissociative recombination of $O_2^+(v)$. Solid lines are computed assuming $k_4 = 1 \times 10^{-10} cm^3 s^{-1}$. Dashed lines are for $k_4 = 6 \times 10^{-10} cm^3 s^{-1}$.

The rate coefficients for production of $O(^1D)$ in reaction (1) reported by Guberman decrease by only about a factor of two from the ground state to vibrational levels $v = 1$ and 2 /8/. Consequently, the computed yields of $O(^1D)$ vary only from about 0.9 to 1.4 over the entire altitude range of interest. Some uncertainty in the yield arises from the use of a single experimental rate coefficient for total dissociative recombination. The total rate probably varies with vibrational level, but unfortunately there are no calculations or measurements for individual vibrational levels. The volume emission rates shown in Figure 4 show that the green line emission follows the O_2^+ profile, but the red line is strongly quenched below 150 km. The integrated overhead intensity of the red line is about 46 R for the model ionosphere chosen, significantly more than the upper limit placed on the intensity from the non-detection by the Venera spectrophotometers. The uncertainties in the $O(^1D)$ yield are much less than those for $O(^1S)$ and the derived values are close to those derived from terrestrial studies (e.g. /28,29/). A detailed calculation of the intensity expected from auroral production has not yet been done, but a local energy deposition calculation suggests a column excitation rate of more than $2 \times 10^8 cm^{-2} s^{-1}$. Most of the auroral electrons are predicted to deposit their energy between 140 and 150 km, so most of the excited atoms will be quenched before radiating. The limit on the red line emission from Venera measurements is problematic for the nightglow as well as for the aurora. The variability of the ionosphere is, however, large enough that a single measurement may not be representative of average values. D. M. Hunten (private communication, 1987) has initiated efforts to observe the red line on the Venus nightside from the ground in conjunction with PVO Ultraviolet Spectrometer measurements of the uv aurora. If the problem with scattered light from the dayside proves intractable, resolution of the issue may have to await measurements made by a visible spectrometer on an orbiting spacecraft.

ACKNOWLEDGEMENTS

This work has been supported in part by grant ATM 8700436 from the National Science Foundation to the Massachusetts Institute of Technology and by grants NAGW-665 and NAG2-329 from the National Aeronautics and Space Administration to the Research Foundation of the State University of New York at Stony Brook.

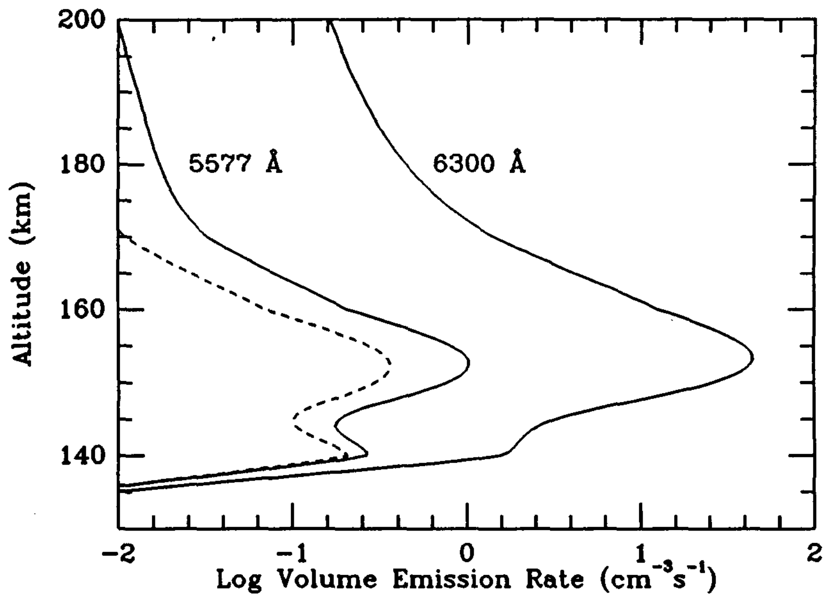

Fig. 4. Altitude profiles of the volume emission rates of the red and green lines of atomic O. Solid lines are computed assuming $k_4 = 1 \times 10^{-10}\mathrm{cm}^3\mathrm{s}^{-1}$. The dashed line is for $k_4 = 6 \times 10^{-10}\mathrm{cm}^3\mathrm{s}^{-1}$.

REFERENCES

1. J. L. Phillips, A. I. F. Stewart and J. G. Luhmann, *Geophys. Res. Lett.* 13, 1047 (1986)
2. J. L. Fox and A. I. F. Stewart, *in preparation* (1988)
3. W. C. Knudsen and K. L. Miller, *J. Geophys. Res.* 90, 2695 (1985)
4. K. I. Gringauz, M. I. Verigin, T. K. Breus, and T. Gombosi, *J. Geophys. Res.* 84, 2123 (1979)
5. V. A. Krasnopolsky, *Planet. Space Sci.* 29, 925 (1981)
6. V. J. Abreu, R. W. Eastes, J. H. Yee, S. C. Solomon and S. Chakrabarti, *J. Geophys. Res.* 91, 11365 (1986)
7. S. L. Guberman, *Nature* 327, 408 (1987)
8. S. L. Guberman, *Planet. Space. Sci.* 36, 47 (1988)
9. A. E. Hedin, H. B. Niemann, W. T. Kasprzak and A. Seiff, *J. Geophys. Res.* 88, 73 (1983)
10. S. J. Bauer, L. M. Brace, H. A. Taylor, T. K. Breus, A. J. Kliore, W. C. Knudsen, A. F. Nagy, C. T. Russell and N. A. Savich, *Adv. Space Res.* 5, 233 (1985)
11. W. C. Knudsen, K. Spenner, K. L. Miller and V. Novak, *J. Geophys. Res.* 85, 7803 (1980)
12. W. C. Knudsen, K. Spenner, and K. L. Miller, *Geophys. Res. Lett.* 8, 241 (1981)
13. T. E. Cravens, S. L. Crawford, A. F. Nagy and T. I. Gombosi, *J. Geophys. Res.* 88, 5595 (1983)
14. K. Spenner, W. C. Knudsen, R. C. Whitten, P. F. Michelson, K. L. Miller and V. Novak, *J. Geophys. Res.* 86, 9170 (1981)
15. H. A. Taylor, R. E. Hartle, H. B. Niemann, L. H. Brace, R. E. Daniell, S. J. Bauer and A. J. Kliore, *Icarus* 51, 283 (1982)

16. W. C. Knudsen, K. L. Miller and K. Spenner, *J. Geophys. Res.* 91, 11,936 (1986)

17. T. E. Cravens, L. H. Brace, H. A. Taylor, C. T. Russell, W. L. Knudsen, K. L. Miller, A. Barnes, J. D. Mihalov, F. L. Scarf, S. J. Quenon and A. F. Nagy, *Icarus* 51, 271 (1982)

18. H. A. Taylor, H. C. Brinton, S. J. Bauer, R. E. Hartle, P. A. Cloutier and R. E. Daniell, *J. Geophys. Res.* 85, 7765 (1980)

19. J. L. Fox, *Adv. Space Res.* 5, 165 (1985)

20. H. Böhringer, M. Durup-Ferguson, E. E. Ferguson and D. W. Fahey, *Planet. Space Sci.* 31, 483 (1983)

21. J. L. Fox, *Planet. Space Sci.* 34, 1252 (1986)

22. E. Alge, N. G. Adams and D. Smith, *J. Phys. B.* 16, 1433 (1983)

23. W. C. Knudsen, K. L. Miller, K. Spenner, *J.Geophys. Res.* 91, 11,936 (1986)

24. J. L. Fox, *EOS (Trans. Am. Geophys. Union)* 68, 1392, (1987)

25. A. F. Nagy, T. E. Cravens, S. G. Smith, H. A. Taylor and H. C. Brinton, *J. Geophys. Res.* 85, 7795 (1980)

26. J. E. Frederick, D. W. Rusch, G. A. Victor, W. E. Sharp, P. B. Hays and H. C. Brinton, *J. Geophys. Res.* 81, 3923 (1976)

27. J. P. Kopp, J. E. Frederick, D. W. Rusch and G. A. Victor, *J. Geophys. Res.* 82, 4715 (1977)

28. P. B. Hays, D. W. Rusch, R. G. Roble and J. C. G. Walker, *Rev. Geophys. Space Phys.* 16, 225 (1978)

29. R. Link, J. C. McConnell and G. G. Shepherd, *Planet. Space Sci.* 29, 589 (1981)